Magnet-free Non-reciprocal Graphene Metasurfaces at THz Frequencies

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Recently, there has been a lot of interest in the design of magnet-free nonreciprocal devices, in order to avoid the problems related to the use of magnetic materials and magnetic biasing, including large size, large weight and incompatibility with integrated circuit technology. So far, most of the efforts have focused on the design of devices for guided waves, including isolators and circulators, for applications in full-duplex communication systems and the protection of sources from undesired reflections. On the other hand, very little work has been performed on non-reciprocal devices for waves propagating in free space, despite the fact that such devices can find important applications in the design of protective layers for sensitive equipment or routing of waves in free space.

Here, we target this problem and propose magnet-free non-reciprocal metasurfaces at THz frequencies based on graphene. Our approach is based on the concept of angular-momentum biasing, according to which breaking reciprocity is possible by imparting angular momentum to a circuit, either mechanically or electronically through appropriate modulation of its parts in space and time. A particularly attractive implementation of this approach, due to its simplicity and high efficiency, consists in a system of three identical resonators, symmetrically coupled to each other and modulated in time with signals of the same amplitude and a phase difference of 120 deg. This technique has been successfully used for the realization of compact and efficient circulators at microwave frequencies. Here, we follow the same technique in order to design nonreciprocal metasurfaces that provide isolation for circularly-polarized waves at THz frequencies. The proposed metasurfaces are based on unit cells consisting of triads of resonant graphene patches modulated in space and time as described above. Graphene has been selected as the material of the resonators for its exceptional interaction with THz waves and unique modulation capabilities. Without modulation, such a metasurface supports circularly-polarized modes with the same frequency. Modulation breaks the degeneracy of such modes and allows designing metasurfaces that are absorptive for one type of circular polarization and reflective for the other one. We analyze this structure through coupled-mode theory and derive the conditions for optimum response. Furthermore, we show that, contrary to the most widespread view that loss is a parasitic effect that generally degrades the performance of devices, in this case the inevitable loss of graphene can be used to our advantage, allowing under proper design to achieve very large (theoretically infinite) isolation and relatively small insertion loss. Our results open a new path in the design of non-reciprocal metasurfaces, show the great potential of graphene for the design of modulated devices at THz frequencies, and point towards a new direction of non-reciprocity through spatiotemporal modulation of the loss properties of materials.